Oscilloscope Probing Your Satellite

When designing space electronics, particularly during the early prototyping stage or if qualification or flight hardware doesn't function as intended, the humble oscilloscope is often used to verify the presence, timing and quality of key signals.

When debugging your space electronics using an oscilloscope, many different measurement types are now possible, *e.g.* analogue voltages, currents, power rails, digital logic, EMC, optical, TDR and high voltage. For each of these applications, the specification of the probe that makes contact with your DUT determines the quality of your test, *e.g.* its frequency response and bandwidth, how it loads the DUT, does it match the input impedance of your scope, where and how you attach the signal and ground contact tips. Often the probe is overlooked or taken for granted, and during visits to customers, many times I have seen the wrong diagnosis because of poor probing technique or incorrect decision making because of the specification of the oscilloscope and/or probe. Ultimately this has impacted the ability of clients to deliver hardware and sub-systems to cost and schedule.

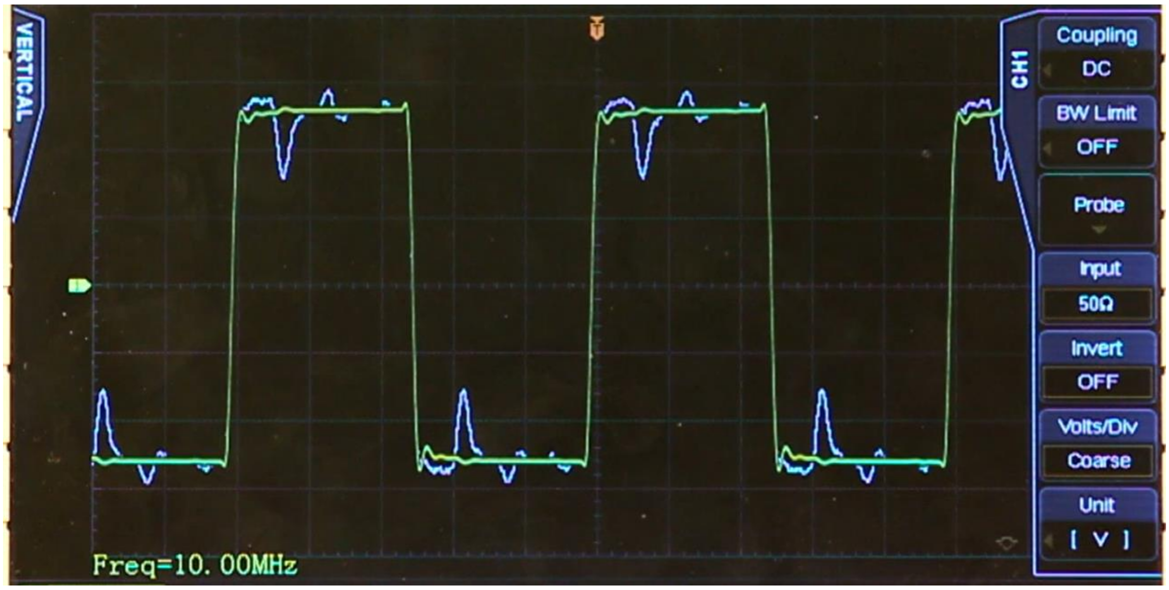
An ideal probe would not load the DUT, transmit the signal under investigation from its tip to the oscilloscope with perfect fidelity, have zero attenuation, zero capacitance, zero inductance, infinite bandwidth and linear-phase characteristics at all frequencies.

In reality, a probe is a circuit with its own electrical characteristics and when it makes contact with your DUT, it suddenly becomes part of a larger system with its specification combining with that of the circuit of interest. To make a measurement, the probe must 'steal' some energy from the DUT and transfer this to the scope's inputs in a way not to load the DUT, to prevent degradation of the signal to be measured, nor impair the normal functioning of the DUT. Probes and oscilloscopes have an inherent capacitance creating a low-pass filter that impacts higher frequencies, *i.e.* bandwidth, slowing rise times. Probes have an intrinsic resistance, forming a voltage divider which reduces signal amplitude. Leads attached to probes add unwanted inductance resulting in overshoot and ringing on the display, or can act as antennae picking-up electrical noise from the surrounding environment. None of these effects may actually be present in the signal you are trying to measure, so it's not a surprise if tests are misleading and the diagnosis wrong!

For general-purpose testing, the key is to use probes which have a high input resistance to minimise the current taken from the DUT, typically 1 to 10 MΩ, as well as low input capacitance to ensure high impedance at higher frequencies, usually 10 to 30 pF. A low impedance would adversely load the DUT impacting the measured signal level.

As frequencies rise, to avoid reflections due to capacitive and inductive reactances, the source, load and probe characteristic impedance should be matched, usually 50Ω. As a guide, an interconnect can be considered a transmission line potentially susceptible to reflections if its time delay *i.e.* its critical length, is greater than one third the signal rise time.

Figure 1 compares the signal integrity measured from a 10 MHz clock using both 1 MΩ and 50Ω input impedances. The former (light blue trace) contains reflections while the fidelity of the latter (green trace) is superior!



Coupling DC
BW Limit OFF
Probe
Input 50Ω
Invert OFF
Volts/Div Coarse
Unit [V]
Freq=10. 00MHz

Figure 1 : The difference in signal integrity due to oscilloscope input impedance.

Although I still have several, it's rare for me to use the much-abused, 50Ω, BNC oscilloscope coax cable with crocodile clips to accurately test and measure the latest space electronics. However, occasionally I do: the question is, when can you use this $10 'probe' rather than the expensive $10k ones?

Last week I had an FPGA that wasn't communicating with its JTAG programmer and needed to check the board was receiving the TCK, TMS and TDI inputs, and outputting TDO. All the expensive, sexy probes were being used, however, due to the low frequency of the JTAG signals, I knew the trusted 50Ω, BNC coax cable could verify these signals with good integrity.

Figure 2 : The ubiquitous, 50Ω, BNC oscilloscope coax cable found in most labs.

Today's satellite and spacecraft electronics operate at higher frequencies, with digital signals having faster edges and lower voltages, close to larger switching currents and sensitive analogue signals. Many small satellites squeeze all these functions onto one tiny PCB. To accurately measure signals, observe events and make the correct decisions, the specifications of the probe and the oscilloscope become paramount, in particular bandwidth, when choosing the right test equipment.

From Fourier analysis, the bandwidth of a digital signal with a 50% duty cycle and a 10 to 90% rise time can be approximated by:

$$Bandwidth\ (GHz) = \frac{0.35}{Rise\ Time\ (ns)}$$

You might not know the edge rates of the digital signals you may have to measure in the future, but if you have an appreciation of the highest frequency of interest, *e.g.* a clock, an estimate of rise time and hence bandwidth can be calculated. For example, if one assumes rise time comprises 7% of the total period, the signal bandwidth can be estimated as, ***5 * Fclk***, *i.e.* up to the fifth harmonic!

Knowing the maximum signal frequency allows you select the appropriate oscilloscope and probe bandwidths for accurate measurements. To minimise the in-band effects of their respective 3 dB amplitude roll-offs, these should be 3 to 5 times higher than the largest harmonic contained within the signal of interest.

As an example, for a sine wave with a fundamental frequency of 700 MHz, the oscilloscope and probe bandwidths should each be between 2.1 and 3.5 GHz. Likewise for other analogue signals such as modulated carriers, choose bandwidths at least three times larger than its highest frequency component.

For a digital signal with an edge rate of 0.5 ns, its resulting bandwidth can be approximated by 0.35 / 0.5 = 700 MHz. The measurement bandwidth of the scope and probe should be between 2.1 and 3.5 GHz to accurately capture the fidelity of the fifth harmonic. Similarly for rise and fall times, if you want to accurately see these transitions, the edge rates of your probe and oscilloscope should be three to five times faster the signal of interest. If you want to validate the specifications of your instrumentation, input a pulse that has rise/fall times three to five times faster!

The following figures illustrate the impact of oscilloscope bandwidth on measurement fidelity when verifying a 100 MHz clock with 500 ps edges: a 100 MHz scope only passes through the fundamental frequency while a 500 MHz one captures up to the fifth harmonic preserving the intended waveform, but its own rise time specification is limiting the measurement of the actual signal edge rate. A 1 GHz scope has 20% accuracy while a 2 GHz one offers 3%.

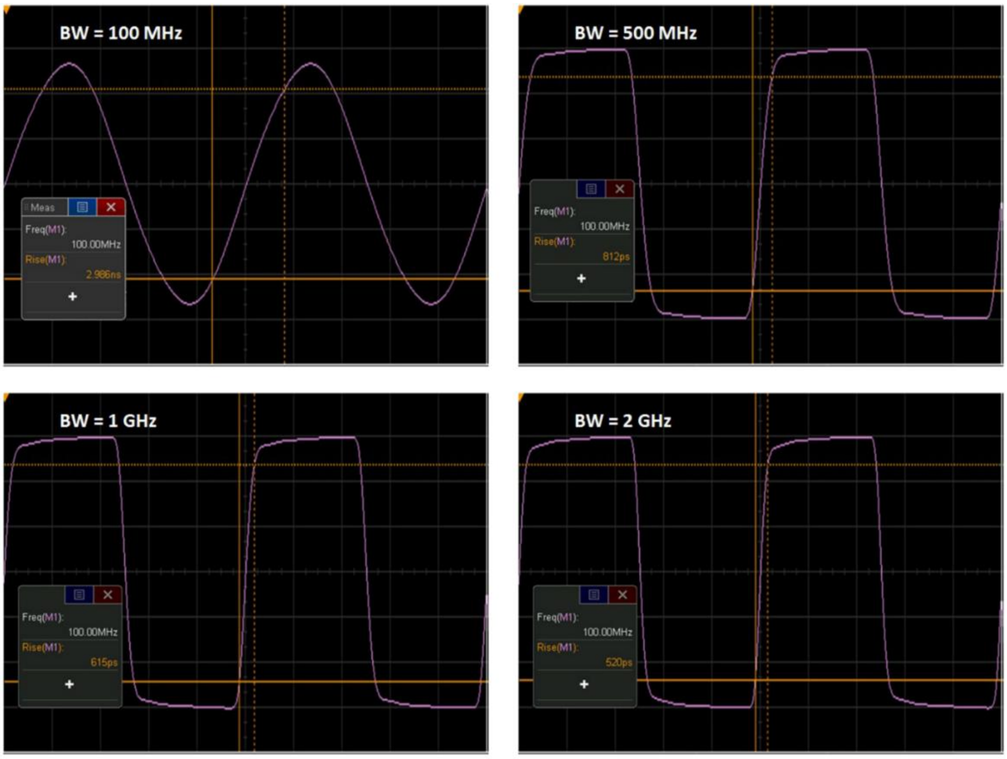


Figure 3 : Impact of scope bandwidth on waveform fidelity and rise-time [Keysight].

A word of caution, there is such a thing as too much bandwidth as measurements can pick-up high-frequency noise as shown below, impacting system ENOB. The 20 MHz waveform on the left was captured using a bandwidth of 6 GHz, while the one on the right had 100 MHz. Use the lowest bandwidth possible while still having enough to accurately capture the frequencies contained within your signal of interest. If possible, limit measurement bandwidth using the oscilloscope's built-in hardware or software filters, and/or the specification of the probe.

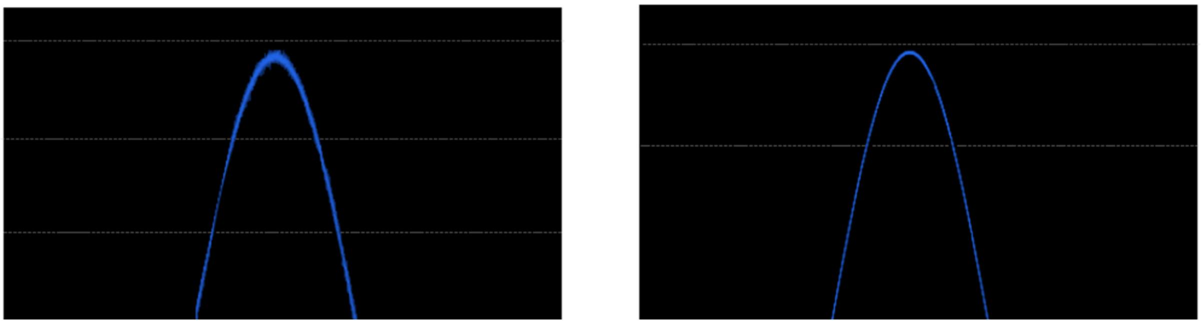


Figure 4 : Impact of too much measurement bandwidth on waveform noise [Keysight].

Going back to my problem of debugging the uncommunicative FPGA using a one metre, 50Ω, BNC coax cable as a probe, how did I know this would be fine for verifying the JTAG signals? The delay the signal experiences as it travels down the one metre cable is approximately 5 ns. For rise times longer than 3 * 5 ns = 15 ns (critical length), the resulting bandwidth can be approximated by 0.35 / 15 ns = 23 MHz. The fundamental frequency of the JTAG signals is around 1 MHz, *i.e.* well below 23 MHz, with a sufficient number of odd harmonics (bandwidth) captured to display the waveforms with good integrity and sharp edges. I also knew the BNC cable has a bandwidth of at least 1 GHz and the oscilloscope 8 GHz. Don't trash those $10 cables just yet!

Many different types of probes can be used with modern digital oscilloscopes enabling a variety of measurement types: firstly, should you choose a passive or an active probe? The former are often shipped with oscilloscopes, are lower cost, rugged and good for general-purpose testing often up to several hundred MHz. Internally these only contain passive components that respond to the signal being measured.

Passive probes have an attenuation factor that impacts DUT loading and the measurement bandwidth: a 1x or 1:1 probe does not change the input amplitude offering better sensitivity for low-voltage signals, whereas a 10x reduces the input magnitude by a factor of ten. These are used to protect the oscilloscope's maximum rated voltage and offer better SNR as any noise picked up by the probe is also attenuated, thus improving signal quality. The use of a 10:1 probe results in higher internal resistance, typically 10 MΩ compared to 1 MΩ, which reduces circuit loading. The addition of capacitance in the tip cancels the scope's input capacitance, increasing bandwidth and improving the measurement of higher frequencies and faster edges.

Check whether your oscilloscope auto-senses the probe attenuation or whether you have to manually switch between these. Passive probes also come with compensation to match the probe and oscilloscope input impedances. Without adjustment, the capacitive loading of the probe may filter out high-frequency components and distort the signal under investigation.

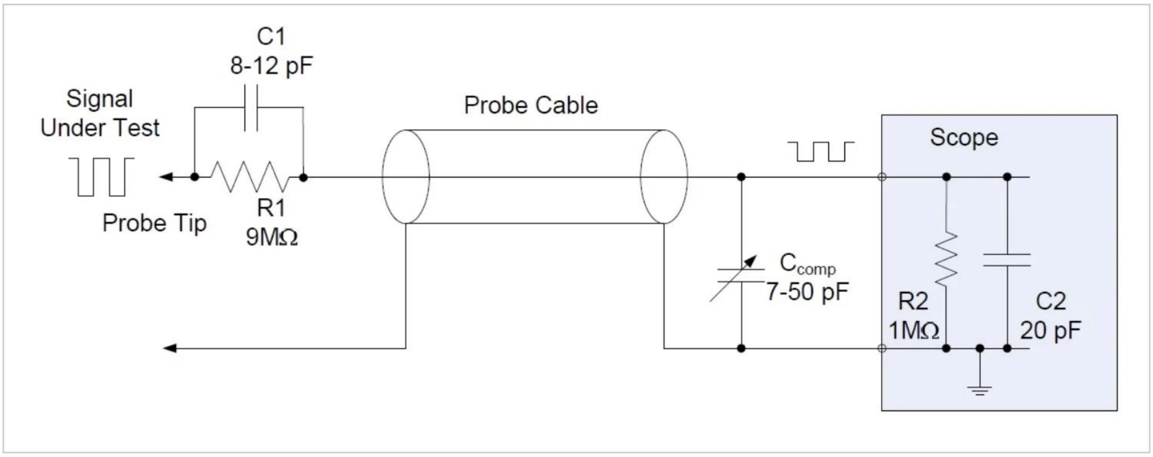


Figure 5 : Typical schematic of a 10x passive probe.

At frequencies beyond 500 MHz, the output capacitance of most passive probes degrades the higher harmonics and edge rates. Furthermore, they can severely load the DUT as the oscilloscope's input impedance is not significantly higher than the circuit's output impedance. Active probes do not use signal power from the DUT, but alternatively utilise wideband amplifiers to enable high-frequency measurements. Active probes have high input resistance and low capacitance, typically less than 1 pF, offering bandwidths up to 20 GHz.

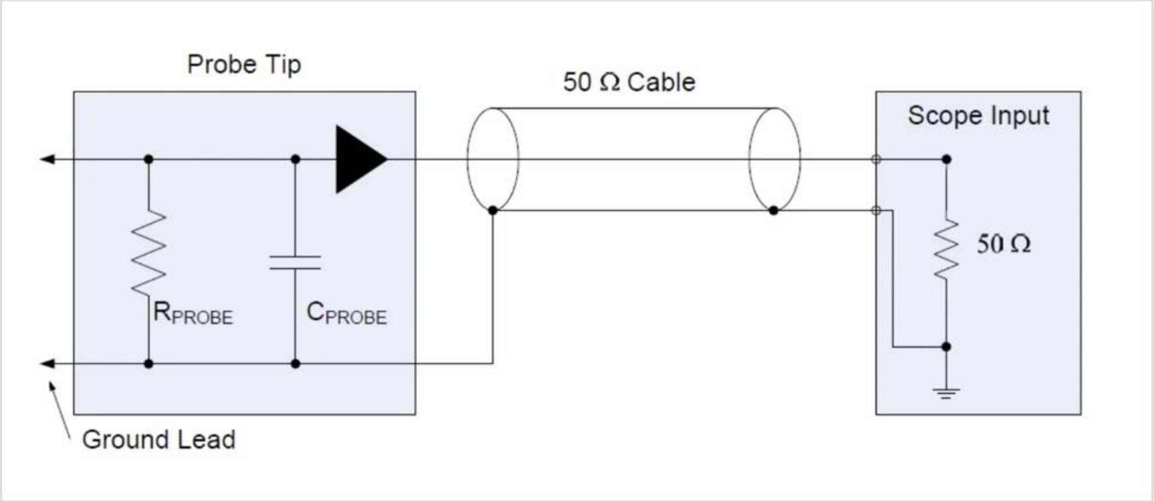


Figure 6 : Typical schematic of an active probe.

The above are single-ended, measuring a signal with respect to ground: differential probes measure the potential difference between any two points and are suitable for verifying low-amplitude, high-frequency I/O such as LVDS as used by many Earth-Observation imagers. Differential probes offer high common-mode rejection over a broad range of frequencies and use an internal differential amplifier to convert the difference between two inputs into a voltage that can be sent to a typical single-ended scope input.

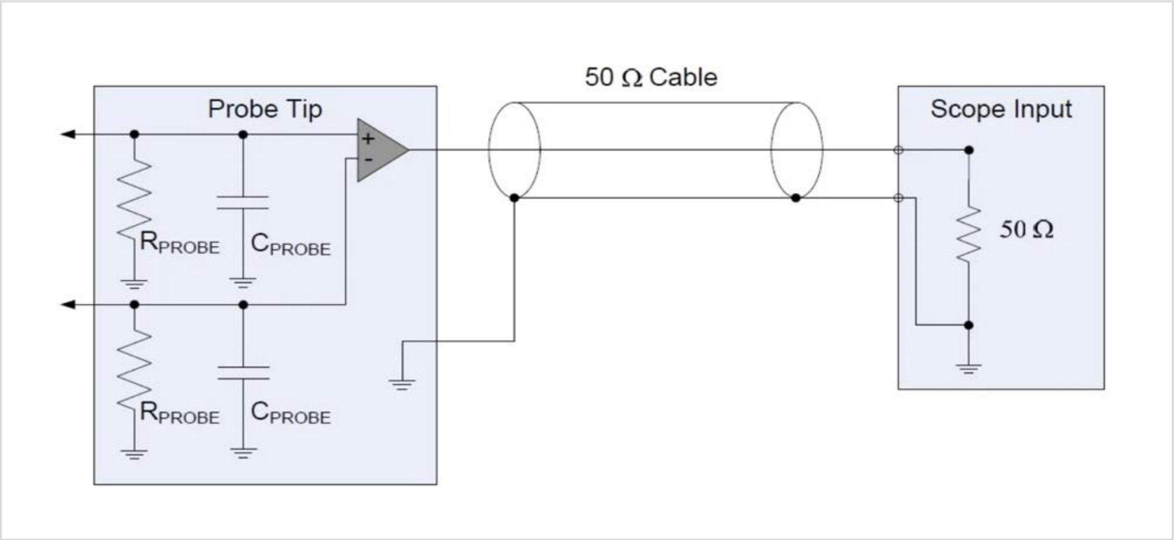


Figure 7 : Typical schematic of a differential probe.

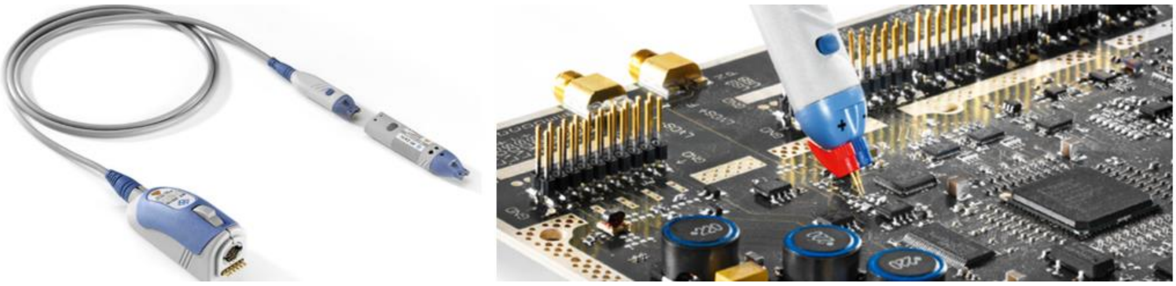


Figure 8 : Active differential probe [Rohde & Schwarz].

Power-rail probes allow you to measure a.c. ripple, high-frequency noise and transients at high bandwidths on supply voltages with large d.c. offsets, and then analyse the spectrum of this interference. EMC probes enable E & H near-field debugging of EMI issues, while current probes provide a non-invasive method for measuring current flow through a conductor. A d.c. probe uses a hall-effect sensor to detect the magnetic field generated by a current as it passes through the probe’s ferrite core, while an a.c. probe uses a transformer to measure current flow through its core.

The Figure below shows a recent current measurement from an Earth-Observation payload to verify its in-rush behaviour at power-up. Thank you to my friends Giovanni and Nick from Rohde & Schwarz UK for helping me with this test.

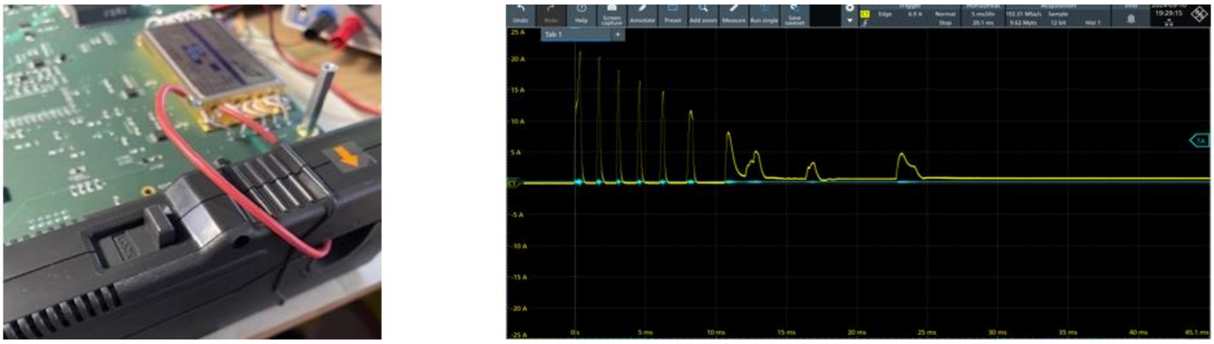


Figure 9 : Oscilloscope current probe measuring payload in-rush current at power-up.

One issue often overlooked is the parasitic effect of the tips probing the DUT, known as the 'connection bandwidth'. How and where you probe is equally as important as the specification of your test equipment: long connections degrade the measurement bandwidth, slowing edges, as well as adding unwanted inductance, resulting in ringing and distortion when measuring high-frequency signals. These may not actually exist in the circuit under investigation! Parasitic components to the left of the point labelled *VAtn* below determine the quality of the actual measurement.

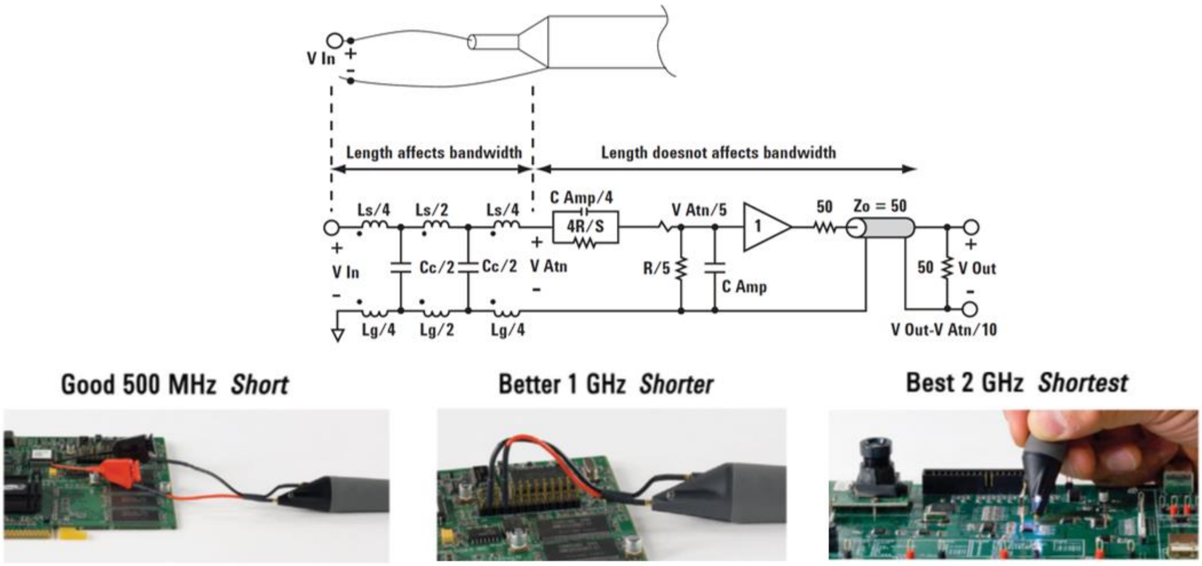


Figure 10 : The impact of probe-tip length on measurement bandwidth [Keysight].

Here's my Top Tips when considering oscilloscope probes to test your space electronics:

1. Before choosing a probe, understand the statistics of the signals to be measured, *e.g.* the amplitude, frequency, bandwidth and edge rates, and then specify the probe as described.
2. Ensure the probe is compatible with your scope's input impedance
3. Ensure the probe does not adversely load the DUT and compensate passive probes.
4. For single-ended probing, do not confuse the signal and ground measurement points – I did this once and killed an FPGA!
5. Ensure the probe has a better or comparable bandwidth to the oscilloscope.
6. Use short leads/tips to maximise probe bandwidth and minimise parasitic components.
7. Specify the required measurement bandwidth, but avoid too much to minimise noise.
8. Check common-mode rejection before testing.
9. Consider its ergonomics/physical design, order a holding fixture if you run out of hands!
10. Keep a few traditional BNC cables in the lab. in case your colleagues won't share.

To conclude, the humble oscilloscope is often used to verify the presence, timing and integrity of key signals during the early prototyping stage or if qualification or flight hardware doesn't function as intended. Many different tests are now possible using your scope and choosing the correct probe, understanding how its specification reconciles and interacts with your DUT, its parasitic effects, how and where it is used, will all impact the quality of your measurements.

We could probe further 😊, but I'm off to the lab: until next month, the person who shares their best oscilloscope probing story will win a Spacechips' Training World Tour tee-shirt.

Spacechips will be teaching its training course, Testing Satellite Payloads, next year and you can contact, events@spacechipsllc.com, for more information.